Proactive Access Point Driven Handovers in IEEE 802.11 Networks

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***Abstract*—In large and densely deployed IEEE 802.11 networks, a fast and seamless handover scheme is an important aspect in order to provide reliable connectivity for mobile users. However, IEEE 802.11 only supports decentralized, reactive and mobile node-driven handovers resulting in long handover times, packet loss due to interrupted connectivity and sub-optimal access point selection. Recently, centralized approaches have been developed that try to solve many of the challenges but these are mostly proprietary, reactive and require changes to mobile node stacks. In this paper, we propose a novel handover solution based on the principle of Software Defined Networking, that addresses the aforementioned challenges. Using virtualization and softwarization, we shift the traditional mobile node-driven handovers to the access point, while maintaining compliance with legacy devices. Moreover, we develop a proactive handover algorithm ADNA, which combines network state, traffic load and node mobility information. We evaluate our approach extensively in a testbed, showing that it outperforms existing approaches by improving the overall throughput by 116% while reducing the number of handovers by 44% on average.**

I. Introduction

IEEE 802.11 [1] (Wi-Fi) networks have boomed in recent years, creating large and dense multi access point environments. A crucial part of IEEE 802.11 is the handover process, which occurs when a mobile node, Station (STA), moves its association from one Access Point (AP) to another, typically triggered by the node moving out of coverage range of the AP. In standard IEEE 802.11, the handover process is node-driven, reactive and based on a single metric - Received Signal Strength Indicator (RSSI). Once the RSSI value between the STA and AP drops below a certain threshold, the STA disconnects from the current AP. It then scans for neighboring APs and selects the one with the highest RSSI value. This whole process can take up to 4 seconds because it involves switching to different channels and waiting for beacon frames to collect RSSI values or actively probing surrounding APs on a given channel [2].

Although different optimizations are possible to reduce the scan time, several problems arise. First, most STA-driven handovers are reactive leading to poor Quality of Service (QoS) for a long duration of time. Although solutions are available that try to virtually connect to multiple APs simultaneously [3], [4], they require changes to the STA's architecture. Ideally, handover decisions should be proactive taking into account e.g. the distance information between STAs and APs, [5]. Second, STA-driven handover algorithms can utilize only the metrics available at the STA, but the achievable throughput depends also on other factors such as the channel load.

Recently, centralized IEEE 802.11 management systems gained popularity because they allow for more optimal handover decisions as a more global view on the network is possible. Many of those solutions are, however, proprietary, [6], [7], [8], [9], [10]. They focus on the enterprise market or on managing the APs and ignore AP selection procedures for STAs. Other centralized approaches do not take into account node's mobility or location information [11], [12], [13], [14].

In this paper, we propose a proactive solution to handovers in IEEE 802.11 which exploits the mobility of STAs. Our solution does not wait for QoS parameters to deteriorate to trigger the handover process, but rather attempts to predict expected QoS parameters. Based on such a prediction, we trigger a proactive handover to preserve the QoS parameters. Next, using virtualization and softwarization, we shift the handover process from mobile-node driven to centralized AP driven. We do this in a way in which the STA is not aware of a handover being done and which requires no modifications to the STA. This way, any device that supports the IEEE 802.11 standard will be compatible with our solution and we are able to exploit much more network side information, which can provide greater insight when choosing to which AP a STA should be handed over to. So, for the AP selection part of the handover algorithm we gather information such as the locations and traffic loads of the APs, as well as information on the STAs, such as their locations, mobility and traffic.

In this paper we present a proactive handover algorithm, ADNA. The algorithm uses multiple metrics in the AP selection process of the handover, such as the location and mobility information of APs and STAs, predicted future location of the STAs, traffic information of the STAs and their impact on the traffic load of the APs, as well as the RSSI values between STAs and APs. These metrics are fed into a Multi Criteria Decision Making (MCDM) algorithm, which ranks the APs for the STAs based on all the above-mentioned metrics. This ranking information is then used to optimize the traffic load of the APs in a global way, as opposed to making per-device optimizations.

II. Related Work

Recently, there has been important research in moving the intelligence of the handover and the AP selection algorithm to a centralized controller. Murty et al. have proposed one such architecture, [15], but only theoretically. In Dyson [16] and DenseAP [11], the focus of the work is on moving the intelligence from the APs to a centralized controller, and, at the same time, improving the overall throughput in the network. They define a set of APIs that allow clients and APs to send information such as radio channel conditions to a central controller. However, Dyson does not take into account the STA's mobility and mostly relies on a few metrics. DenseAP adds localization awareness but only focuses on very limited movement as the location is only updated every 30 seconds. Bayhan et al. [17] presented a similar approach of using a centralized controller and aiming to maximize the overall throughput using different metrics such as AP-STA link rates, throughput demands of STAs, etc. However, they still rely on the standard IEEE 802.11 handover mechanism and do not take into account the STA mobility. Broustis et al. [18] and Ahmed et al. [19] presented MDG and SMATRA, respectively. Both take different metrics into account for AP selection, such as power control and STA association information. However, they rely on the standard IEEE 802.11 handover mechanism. A number of research papers have also used the centralized approach to the AP selection problem, like [12], [13] and [14], but they do not take into account the location information of the STA and use simulations only to evaluate their work.

Researchers have also tried to tackle the additional latency of the standard IEEE 802.11 handover mechanism. Kawada et al. in [4] use virtualized wireless NICs to be able to achieve that a STA is connected to multiple APs at the same time and in this way, avoid handovers. However, this requires additional overhead. Suresh et al. in [20] propose creating abstractions for the AP and STA which allowed seamless handovers, but taking into account only one metric, the RSSI, to trigger the handover and the mobility informations is not taken into account.

As can be seen, there has been extensive research to move the AP selection and handover procedures to a centralized controller. This enables us to have a global view of the network and to create smarter decision in term of associating STAs to APs. However, a lot of the work is only theoretical or evaluated only in simulation, without real-world implementation. Also, research in this direction has mostly been focusing on the AP selection algorithms, but relying on the standard IEEE 802.11 handover mechanism. As Zubow et al. have stated in [2], this handover procedure can take up to 4 seconds, and seconded by Marquez-Barja et al. in [21]. Most of the work tries to optimize the overall throughput of the network. To accomplish this, some only use one metric. Others, include multiple metrics, but mostly lack the location information. Even if the location information is taken into account, the mobility of the STA and its predicted future location are not being taken into account. Additionally, other researchers rely on modifications to the STA itself to accomplish their centralized approach.

III. Towards Seamless SDN-driven Handovers

We consider an IEEE 802.11 network that consists of multiple APs. In such networks, due to the mobility of the STAs, there is a frequent need to perform handovers. A handover is typically triggered by the STA in a reactive way, meaning the QoS parameters are already degraded at the time of an handover. Once the handover is triggered, the STA scans the channels for beacons and ranks the reachable APs only based on the RSSI. Finally, the AP with the highest RSSI value is selected and the STA re-associates to it. Because of the decentralized reactive approach, it is difficult for the STAs to be always connected to the best AP. Therefore, we propose to use a centralized AP driven handover approach, using 5G-EmPOWER [22]. 5G-EmPOWER is a multi-access edge computing operating system which supports lightweight virtualization, and heterogeneous radio access technologies and enables centralized controllers. Based on a Software Defined Networking (SDN) approach, the control is moved from the APs to a centralized controller. On the controller, high-level programming abstractions for both the AP and STA are introduced. Once a STA aims to connect to the network, the 5G-EmPOWER controller creates the STAs abstraction, called Light Virtual Access Point (LVAP) [23]. This abstraction is created on the AP that the STA connects to. A handover occurs when this abstraction is moved from one AP to another, as depicted by Figure 1. Even thought this is triggered by the SDN controller, the datapath is never re-routed to it, so the controller has no impact on the throughput. This makes the LVAP-based handover seamless and transparent to the STA. The STA is not aware of any change happening at network level since its connectivity has not been interrupted while handovering [23].

5G-EmPOWER is used to manage the network and allow a more global view on it. In addition, we extend it with additional features, such as localization and AP load monitoring, to support our proposed proactive handover algorithm. The controller estimates and predicts future user locations and traffic load patterns on the APs. Based on those predictions, the SDN controller calculates an optimal association plan, which is based on ranking the APs for each STA and proactively triggers a seamless handover for those STA. The goal of our approach is to maximize the total QoS as opposed to the STA's individual QoS, while balancing the load across APs. What metrics the SDN controller uses can be found in Table I.

Since our proactive algorithm focus on optimizing the traffic

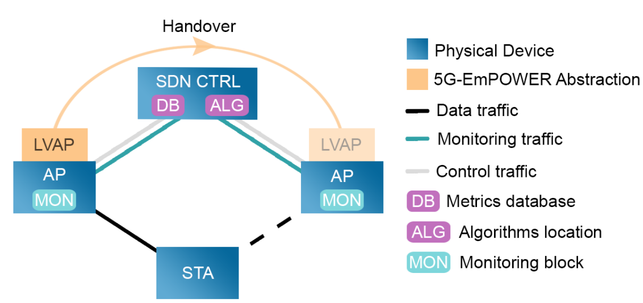

Fig. 1. 5G-EmPOWER Handover concept

load on the APs, the STAs downstream traffic throughput, $r_{sta}(t)$, is monitored. We store the throughput historical and use its average as a reference for predicting the future throughput, $r_{sta}(t+1)$. Each AP in the network has a certain bandwidth capacity, C_{ap}, in terms of the downstream throughput, which is used up by the STAs. The traffic load of an AP is calculated as the sum of throughputs of all the STAs that are associated to that AP.

In order to localize the STAs in an indoor environment, we use the approach of Lim et al. [24]. Their algorithm takes the locations of the APs, l_{ap}, which, considering todays static placement of the APs, can be obtained rather easily, and creates a mapping, T, using a technique called Singular Value Decomposition (SVD) between: (i) the RSSI between each AP and (ii) the distances between each AP, $T : rssi_{ap_i,ap_j}(t) \rightarrow d_{ap_i,ap_j}(t)$. Then, using the RSSI between STAs and APs, the distanced between them can be calculated as: $d_{ap,sta}(t) = T(rssi_{ap,sta}(t))$. More detailed information can be found in [24]. Once the distances between all the nodes in the network (all APs and STAs) are known, an Multi-Dimensional Scaling (MDS) algorithm estimates the locations of the nodes, l_{ap} and $l_{sta}(t)$. The advantage of this localization algorithm in regards to other RSSI ones is that the effects of the wireless physical characteristics are represented by the mapping T and it requires no on-site survey, like in fingerprinting approaches. Another advantage is its simplicity, since it only requires the RSSI to be monitored. However, other localization algorithm may very well be used.

Once the distances and locations of all the APs and STAs are known, we estimate the mobility information of the STA. For each STA we create a so called motion vector, $MV_{sta}(t)$ between the previous and current location of a STA, as its starting and end points, respectively. The length of the $MV_{sta}(t)$ is the distance between those two points, and the angle estimates the direction of the STA's movement. Using this information, the predicted future location can be estimated by assuming that the STA will be moving in the same direction and with the same speed as the current MV.

To take all the metrics into account and rank the potential APs for each STA, we use the Weighted Sum Model MCDM algorithm, [25]. The output of the MCDM algorithm $\forall ap \in AP, \forall sta \in STA$ is a score, $sc_{ap,sta}(t)$, which tells us the preference of STA sta to be handed over to AP ap at time t.

TABLE I
USED METRICS AND THEIR NOTATION

Metric	Notation
Set of (ap, sta), where STA sta is associated to AP ap	$N(t)$
Actual RSSI value between STA sta and AP ap	$rssi_{ap,sta}(t)$
Is the STA sta associated to AP ap	$a_{ap,sta}(t) = \{0, 1\}$
List of reachable APs for STA sta	$ra_{sta}(t)$
The throughput of STA sta	$r_{sta}(t)$
The requested throughput of STA sta	Q_{sta}
Traffic load of AP ap	$b_{ap}(t)$
Capacity of AP ap	C_{ap}
Location of APs and STAs	l_{ap}, l_{sta}
Distance between STA sta and AP ap	$d_{ap,sta}(t)$.

IV. ADNA - PROACTIVE AP DRIVEN HANDOVER

We propose ADNA (see Algorithm 1), which is designed to optimize the load on the AP while also balancing it across APs. ADNA uses 5G-EmPOWER's handover mechanism to avoid the disconnects and drops in throughput that happen during a standard 802.11 handover. Furthermore, it uses the predicted future location of STAs and predicted future AP loads to create an association scheme for all STAs. ADNA first takes a snapshot of the current network state and gathers all the metrics mentioned previously. It initially assumes that all the APs have their full capacity available and starts calculating the MCDM scores based on the metrics and their weights found in Table II. The association parameter gives more preference to the AP that the STA is already connected to, to avoid the ping-pong effect. The RSSI and predicted future location are used to predict where the STA is heading to, so that we can know which APs it will be closest to, as this impacts the throughput that can be achieved. Next, the achievable throughput of the STA also depends on the load of these APs, so we predict what the future load of the APs will be if we decide to handover a STA to a particular AP. We do this by fictionally connecting STA sta to AP ap and calculating the predicted future load of

Algorithm 1 ADNA

N(t)
$\forall ap \in AP, b_{ap}(t+1) = 0$
while STAs to be processed **do**
  for all $sta \in STA$ **do**
    for all $ap \in ra_{sta}(t)$ **do**
      $sc_{ap,sta}(t) = MCDM[rssi_{ap,sta}(t);$
      $d_{ap,sta}(t+1); sta\_dev[b'_{AP}(t+1)]; a_{ap,sta}(t)]$
      if $b_{ap}(t+1) < AVG(\bigcup b_{ap}(t+1))$ **then**
        $sc_{ap,sta}(t) = 1.5 * sc_{ap,sta}(t)$
      end if
    end for
  end for
  for all $sta \in STA$ **do**
    for all $ap \in ra_{sta}(t)$ **do**
      if $(C_{ap} - b_{ap}(t+1) < r_{sta}(t))$ **then**
        $score\_matrix(ap, sta) = 0$
      else
        $score\_matrix(ap, sta) = sc_{ap,sta}(t)$
      end if
    end for
  end for
  Find (ap_m, sta_n) with MAX score in $score\_matrix$
  Add (ap_m, sta_n) to $N(t+1)$
  $b_{ap}(t+1) = b_{ap}(t+1) + r_{sta}(t)$
  Delete sta_n column in $score\_matrix$
  $STA_n \rightarrow Processed$
end while
for all $(ap, sta) \in N(t+1)$ **do**
  $Handover(ap, sta)$
end for

TABLE II
MCDM METRICS USED IN ALGORITHM1

Metric	Criteria	Weight
$rssi_{ap,sta}(t)$	MAX	0.2
$d_{ap,sta}(t+1)$	MIN	0.2
$std\_dev[b'_{AP}(t+1)]$	MAX	0.5
$a_{ap,sta}(t)$	MAX	0.1

the AP. This is then used to find the standard deviation between the future traffic loads of all APs, but with the modified traffic load of the AP at hand, ap. This will show us, how much the future traffic loads will differ if we associate STA sta to AP ap, or better put, what will be the imbalance of future traffic loads across APs. The lower this value is, the better, since it means the traffic load is more balanced across APs. We also add an additional constraint regarding the traffic load. If the $b_{ap}(t+1)$ is lower than the average future traffic load on all the APs, we modify the MCDM score for that ap for all STAs, by a factor of 1.5. This way, we give even higher ranking to the AP with far less load and spread the load more evenly across APs.

Once the MCDM scores are obtained, we create a $score\_matrix$, where the rows represent APs and columns represent STAs. Each element in the matrix, $score\_matrix(ap, sta)$ will be:

$$score = \begin{cases} 0, & C_{ap} - b_{ap}(t+1) < r_{sta}(t) \\ sc_{ap,sta}(t), & \text{otherwise} \end{cases} \quad (1)$$

Next, we find the MAX element in the $score\_matrix$, so (ap_m, sta_n). This element shows us that sta_n has the strongest preference to ap_m. We update the future network state by adding the pair (sta_n, ap_m) to $N(t+1)$. Once we do this, we have to update the future traffic load of ap_m for the next iteration. We update it according to Equation 2.

$$b_{ap_m}(t+1) = b_{ap_m}(t+1) + r_{sta_n}(t) \quad (2)$$

We then loop over the rest of the STAs, but taking into account the predicted future loads of APs, based on the STAs already assigned to them in the previous iterations. Once all STAs have been processed, we use 5G-EmPOWER's LVAP seamless handover mechanism to handover the STAs according to their assigned APs in the future network state.

V. EXPERIMENTAL SETUP

We have evaluated our approach and algorithm by running experiments on top of a large-scale wireless testbed called w-iLab-t, [26], a experimental, generic, heterogeneous wireless testbed for development and testing of wireless applications via an intuitive web-based interface. It is equipped with fixed wireless nodes and mobile wireless nodes, which make it a great environment for testing wireless handovers. These mobile nodes are able to be controlled by setting a path of movement which they follow. The stationary wireless nodes in the testbed are mounted in a $66(m)$ by $20.5(m)$ open room. However, w-iLab-t also limits the transmission power of the wireless nodes to emulate longer distances.

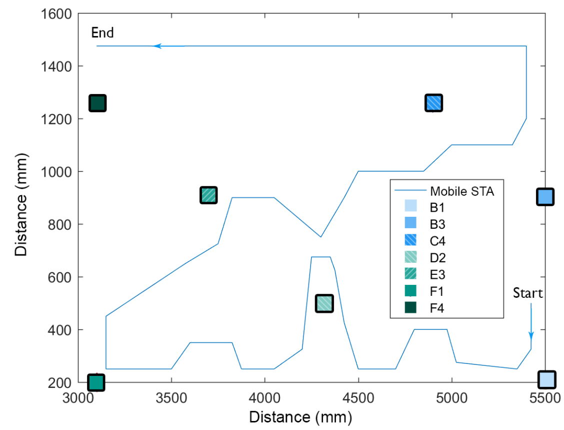

Fig. 2. AP layout and mobile STA movement path

To evaluate our approach we use: (i) 1 fixed node to act as our 5G-EMPOWER Centralized Controller, (ii) 7 fixed wireless nodes to act as our APs all set on channel 36 in the 5GHz band and (iii) 4 mobile wireless nodes to act as mobile STAs that move at the speed of $16(cm/s)$ and establish a $Q_{sta} = 10(Mbps)$ TCP connection. The layout of the APs in the testbed is shown on Figure 2. Each AP has $C_{ap} = 25(Mbps)$ capacity. They are labeled as: B1, B3, C4, D2, E3, F1, F4. For experimental purposes, traffic steering is used at the AP level using the traffic control tool to limit the rate it can serve. The initial traffic load on each AP in $Mbps$ is as follows: B1 - 0, B3 - 22, C4 - 3, D2 - 20, E3 - 24, F1 - 2, F4 - 3.

For our first experiments, we use one mobile STA. Figure 2 illustrates the movement path that our mobile STA will be taking in the experiments. First part of the movement path has the mobile STA go from AP B1, pass by D2 and arrive near F1. The goal is to see whether the algorithm can predict the future location of the STA to be near F1 and avoid handing over the STA to AP D2. Next, the mobile STA moves from near AP F1, passes by D2 and E3, and arrives near APs B3 and C4. The goal is to confirm that the predicted future location will again skip handing over the STA to D2 and E3, but this time it will have two AP to choose from. Here is where the predicted future load of the AP will come in hand, as AP B3 is already overloaded. So, the algorithm should try to avoid handing over the STA to B3, and choose C4 instead. After evaluating that our algorithm works, we move to large scale evaluations with multiple mobile STAs moving in different patterns.

VI. RESULTS DESCRIPTION

To evaluate our approach, we compared ADNA to the IEEE 802.11 standard handover algorithm and to a state of the art proactive, centralized one called MAX RSSI, described in [5], [17], [12], which hands over a STA to the AP with the highest RSSI, regardless of perceived mobility. We first illustrate the results of a single run for all 3 algorithms. Secondly, statistical information on multiple experimental runs is shown in section VI.B, to asses the robustness. Section VI.C illustrates the impact of multiple STAs.

A. Evolution over time

Figures 3, 4 and 5 show the connectivity of the mobile STA along the movement path, as well as the handovers that occurred for all 3 algorithms. The standard 802.11 algorithm triggers 6 handovers, MAX RSSI 9, while ADNA triggers 3. The MAX RSSI algorithm has even more handovers than the standard 802.11 one, since it triggers a handover as soon as there is a new AP with the highest RSSI. However, the MAX RSSI algorithm, as a proactive one, does not experience complete disconnects as the standard 802.11. On the other hand, ADNA makes the least handovers and also does not experience complete disconnects of the STA. It uses the predicted future location to skip handing over the STA to D2, as well as E3, since the STA only passes by them. Also, the load of the APs plays a role when the STA is moving toward the area of APs B3 and C4. Since the predicted future location tell the algorithm the STA will be close to both of them, it chooses the AP which is less loaded, that is AP C4.

Figures 6, 7 and 8 show the throughput of the mobile STA over time for all 3 algorithms. The standard 802.11 handover algorithm experiences drops of throughput to zero during the handovers due to the STA having to disconnect from the current AP and having to scan and re-associate to another AP. Also, since the algorithm does not take into account the load of the APs, the STA occasionally gets handed over to an AP with high traffic loads, such as D2, E3 and B3. The MAX RSSI algorithm is proactive resulting in no disconnections happening, however, since it only takes the RSSI into account, it also hands over the STA to APs with high traffic loads. Since the traffic loads are higher than the mobile STA's throughput request, it leads to a reduced throughput of the mobile STA. However, looking at the proactive handover algorithm ADNA, the mobile STA does not experience reduced throughput due to the fact that the mobile STA is handed over only to the APs with low traffic loads. Also, the handover is triggered before the QoS parameters deteriorate in a proactive fashion, which can be seen on the throughput graphs. Finally, the mobile STA gets handed over to APs which it will be near to, according to the predicted future location, so there is no drop in throughput due to large distances and low RSSIs between the mobile STA and the AP.

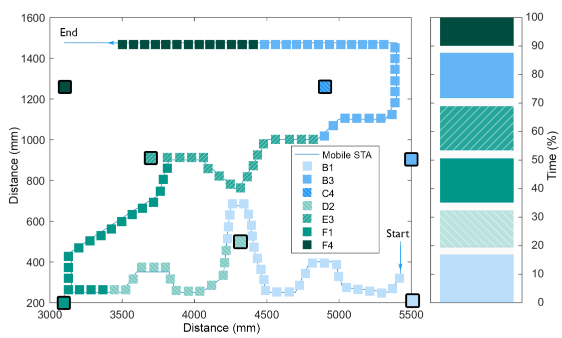

Fig. 3. Standard 802.11 Algorithm Connectivity and handover graph

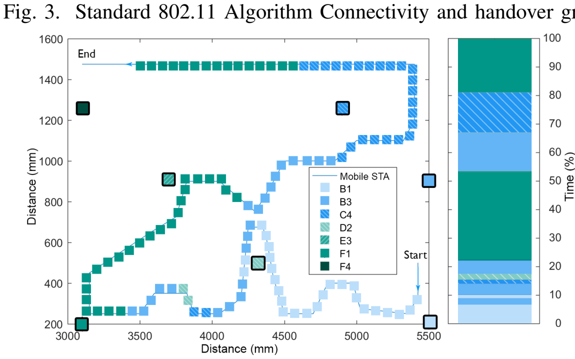

Fig. 4. MAX RSSI Algorithm Connectivity and handover graph

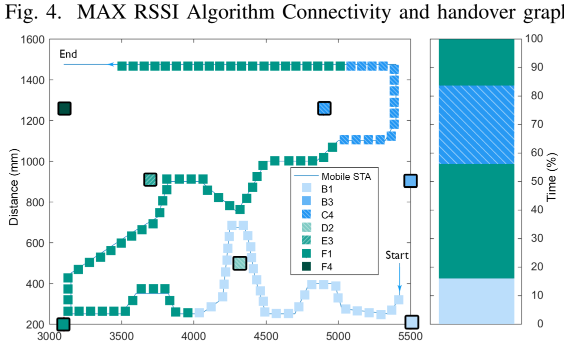

Fig. 5. ADNA Algorithm Connectivity and handover graph

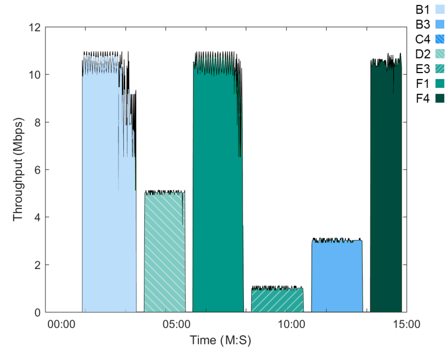

Fig. 6. Standard 802.11 Algorithm Throughput graph

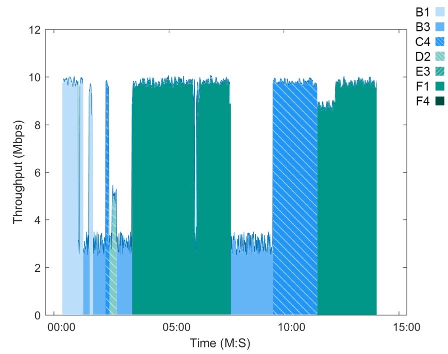

Fig. 7. MAX RSSI Algorithm Throughput graph

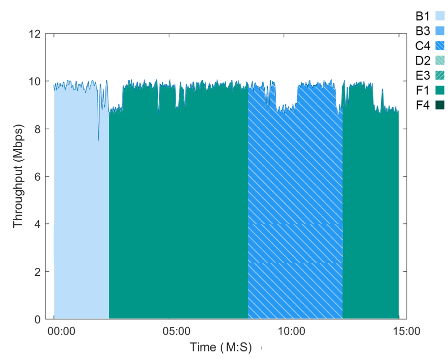

Fig. 8. ADNA Algorithm Throughput graph

B. Robustness Results

While the previous section focused on the impact of a single run, in this section we show the robustness of the approach across multiple runs. Validating the approach was done across 5 runs. Table III shows the average number of handovers. By using the proactive handover algorithm ADNA we were able to reduce the number of handovers by 33% and 51% compared to the standard 802.11 and MAX RSSI, respectively.

TABLE III
AVERAGE NUMBER OF HANDOVERS WITH SINGLE MOBILE STA

Algorithm	Average number of handovers
Standard 802.11 algorithm	5.67
MAX RSSI algorithm	7.83
ADNA	3.33

Figure 9 shows the average throughput of the mobile STA for a number of experimental runs. We can clearly see the reduced throughput with the standard 802.11 and MAX RSSI handover algorithms, as well as its high fluctuations, while ADNA had 38% and 60% higher throughput for the mobile STA compared to the standard 802.11 and MAX RSSI algorithms, respectively.

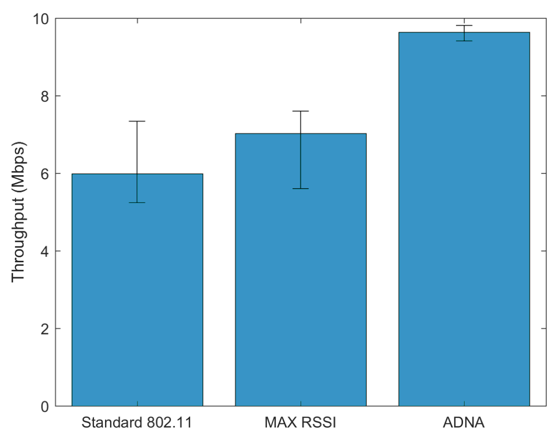

Fig. 9. Average throughput of mobile STA per algorithm

C. Multiple mobile STAs

Finally, we evaluated our approach by having multiple mobile STAs in the testbed, specifically 4 mobile STAs. By repeated experimentation, 5 runs to be exact, we have obtained the average number of handovers triggered by the algorithms. This data is shown in Table IV. As we can see, on average, ADNA has 35% and 44% less handovers than the standard 802.11 and MAX RSSI algorithms, respectively.

TABLE IV
AVERAGE NUMBER OF HANDOVERS WITH MULTIPLE MOBILE STAS

Algorithm	Average number of handovers
Standard 802.11 algorithm	6.63
MAX RSSI algorithm	7.67
ADNA	4.33

Figure 10 shows the average throughput per algorithm in multiple experimental runs, where we can see that ADNA produced a 116% and 24% higher average throughput compared to the standard 802.11 and MAX RSSI handover algorithms, respectively.

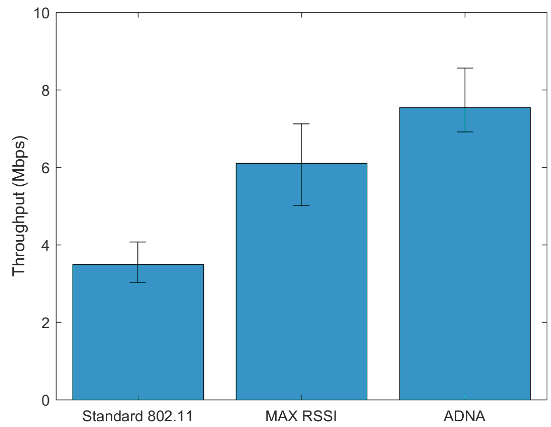

Fig. 10. Average throughput of mobile STAs per algorithm

VII. CONCLUSIONS

In this paper we presented ADNA, a proactive, AP driven handover algorithm within an SDN based, IEEE 802.11 architecture. We utilized 5G-EmPOWER's centralized and seamless handover mechanism which requires no modifications to the STA itself. Our approach does not focus on one metric when deciding to which AP a STA should be handed over to and does not wait for the QoS parameters to deteriorate before making the handover decision. We use the RSSI value, location and mobility information, as well as the traffic information of both the APs and STAs, and feed it to a MCDM algorithm to rank to which AP each STA should be connected to. The results of this paper show that we were able to make proactive handover decisions. We validated our approach on a large scale wireless testbed w-iLabt. We compared our proactive handover algorithm, ADNA, to the standard IEEE 802.11 handover algorithm and a state of the art MAX RSSI. We show how location and traffic information play a role in the handover process. We saw that the our proactive handover algorithm avoids handing over the STA to APs which have high traffic loads. On average, the number of handovers with ADNA were reduced by 35% and 44% when compared to the standard 802.11 and MAX RSSI algorithms, respectively. On the other hand, the average throughput was increased. ADNA increased the average throughput by 116% and 24% when compared to the standard 802.11 and MAX RSSI handover algorithms, respectively.

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